PL-TR-96-2105
Environmental Research Papers, No. 1192

# REPORT ON PHASE BLOCKAGE PHENOMENOLOGY SESSION, SSA 91ST ANNUAL MEETING, 2 APRIL 1996, ST. LOUIS, MISSOURI

Delaine T. Reiter and Rong-Song Jih

5 JUNE 1996





PHILLIPS LABORATORY
Directorate of Geophysics
AIR FORCE MATERIEL COMMAND
HANSCOM AFB, MA 01731-3010

"This technical report has been reviewed and is approved for publication."

JAMES F. LEWKOWICZ
Director
Earth Sciences Division

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or if you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify PL/IM, 29 Randolph Road, Hanscom AFB, MA 01731-3010. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.

| REPORT DOCUMENTATION PAGE | *Form Approved OMB No. 0704-0188* |
|---|---|



| 1. AGENCY USE ONLY *(Leave blank)* | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | 5 June 96 | 1 Apr - 30 Apr 96 |

**4. TITLE AND SUBTITLE**
Report on Phase Blockage Phenomenology Session, SSA 91st Annual Meeting, 2 April 1996, St. Louis, Missouri

**5. FUNDING NUMBERS**
PE 621010
PR 7600
TA 09
WU 08

**6. AUTHOR(S)**
Delaine T. Reiter and Rong-Song Jih

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Phillips Laboratory/ Earth Sciences Division (GPE)
29 Randolph Road
Hanscom AFB, MA 01731-3010

**8. PERFORMING ORGANIZATION REPORT NUMBER**
PL-TR-96-2105
ERP, No. 1192

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

| | |
|---|---|
| HQ AFTAC/TTR | Phillips Lab (GPE) |
| 1030 South Highway A1A | 29 Randolph Road |
| Patrick AFB, FL 32925-3002 | Hanscom AFB, MA 01731-3010 |

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION AVAILABILITY STATEMENT**
Approved for public release; distribution unlimited

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*
This report details the results of a special session on regional phase blockage which was held during the Seismological Society of America's 91st Annual Meeting in St. Louis, Missouri on April 2, 1996. The session consisted of seven orally presented papers by members of the seismic monitoring research community and a follow-up meeting that was intended to be a discussion session about the scientific problem of phase blockage. The report contains the abstracts from the talks, background on regional phase blockage, some results from the papers presented at the session, and some conclusions and recommendations for future research by the authors.

**14. SUBJECT TERMS**
Seismic wave propagation, Phase blockage, Regional seismic monitoring

**15. NUMBER OF PAGES**
26

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

# CONTENTS

# PREFACE

This project was conducted under the auspices of the *Air Force Technical Applications Center* and the *Earth Sciences Division of the Air Force Phillips Laboratory.* The views and conclusions contained in this report are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Air Force or the U.S. Government.

# SUMMARY

A special session on *Regional Phase Blockage Phenomenology* was held on April 2, 1996, at St. Louis, Missouri, during the *SSA 91st Annual meeting.* The session was a result of several discussions between Phillips Laboratory (PL/GPE), AFOSR, and DOE's national laboratories after the *17th Seismic Research Symposium.* The motivation was to gather Comprehensive Test Ban Treaty (CTBT) researchers to review the status and current direction of research on blockage-related topics, and if appropriate, make some suggestions on follow-up topics. The morning session of oral presentations, presided over by Dr. Delaine Reiter (PL/GPE) and Rong-Song Jih (PL/GPE), was followed by a wrap-up discussion that evening convened by Dr. Stanley Dickinson (AFOSR) and Dr. Delaine Reiter (PL/GPE). This report provides some background on regional phase blockage and summarizes the results from the morning session and the issues that were addressed at the discussion session. The seven abstracts presented at the morning session are included in an Appendix to this report with titles of the talks listed below:

1. Baumgardt, $L_g$ *propagation-path barriers in the Eurasian continental craton -- possible shallow crust explanations.*
2. Priestley, Schultz, and Patton, *Anomalous surface wave propagation across the south Caspian basin and the blockage of regional seismic phases.*
3. Jih, McLaughlin, Dainty, and Harkrider, *Numerical modeling of* $R_g$ *blockage and comparison of* $R_g$*-to-*$L_g$ *conversion mechanisms due to scattering and incomplete dissipation.*
4. Xie, $P_n$ *amplitude variation along the northern foot of the Tienshan mountains.*
5. Anderson and Cormier, *Regional variations in* $L_g$ *observed and synthesized at the CNET and KNET arrays.*
6. McNamara, Walter, Schultz, and Goldstein, *Regional phase propagation in northern Africa and the Mediterranean.*
7. Sweeney, *Interpretation of crustal phase characteristics in Iran and the surrounding region determined from ILPA data.*

These papers will be referred to by their title numbers throughout the remainder of this report.

# BACKGROUND INFORMATION

The most prominent regional phase generated by shallow events is the $L_g$ phase identified by Press and Ewing (1952). The $L_g$ phase has received considerable attention in recent years because of its potential use in yield estimation (*e.g.*, Nuttli, 1986) and discriminating between earthquakes and explosions at regional distances (*e.g.*, Blandford, 1981; Pomeroy *et al.*, 1982). Based on empirical observations, $L_g$ has been recognized as a stable relative-yield indicator (Patton, 1988; Hansen *et al.*, 1990). However, it is also recognized that $L_g$, like $R_g$, is sensitive to changes in structure along its path, which can have deleterious effects on any role as a discriminant (*cf.* Lynnes and Baumstark, 1991) or magnitude measure (*cf.* Jih and Lynnes, 1993), unless the propagation effects are accurately accounted for. Numerous studies have used the sensitivity of $L_g$ to structural effects to map regions of anomalous propagation and try to associate them with crustal structure. Bias in $L_g$-based magnitude measurements were reported by Gregersen (1984) in Greenland. Very low $L_g/S_n$ amplitude ratios have been observed after crossing the Tibetan plateau (Ruzaikin *et al.*, 1977), the North Sea grabens (Gregersen, 1984; Kennett *et al.*, 1985), the Caspian Sea or the Black Sea (Levshin and Berteussen, 1979; Kadinsky-Cade *et al.*, 1981). Chinn *et al.* (1980) (and Lynnes and Baumstark, 1991) observed that the efficiency of the $L_g$ propagation is better for paths parallel to the structural trend than for paths in the perpendicular direction. Earlier studies (Press and Ewing, 1952; starkr and Ewing, 1957; Savarensky and Valdner, 1960) have established that $L_g$ does not propagate through crust overlain by water deeper than 2 km. On the other hand, propagation across a marginal sea of continental shelf does not completely quench $L_g$, but can reduce its amplitude. Baumgardt (1991) compared the crustal cross-sections for $L_g$ propagation, and found that the $L_g$ blockage correlates with thick sediment very well. Basically, his observation was that paths that do not cross basins or for which sediments do not vary by greater than 3 km exhibit little or no $L_g$ blockage and scattering. Baumgardt (1991) also identified paths for which the surface elevations and crustal thickness change substantially, and yet $L_g$ propagates efficiently. Thus his observations suggest that the near-surface sediment-thickness variations seem to correlate more strongly with $L_g$ blockage than do the crustal-thickness variations. Zhang and Lay (1994) used surface topography as a manifestation of the varying crustal structures. They found a strong correlation between $S_n/L_g$ ratios for Eurasian explosions and roughness or mean altitude of the topography along the path, based on a meager data set.

Despite the long-time interest, many fundamental questions about the excitation and propagation of $L_g$ waves phases remain to be answered. Numerical modeling of the $L_g$ waves (and other regional phases) would complement the empirical studies by providing more accurate interpretations and better insight of the underlying physics. Theoretical studies of $L_g$ propagation across continental margins have been conducted by Kennett (1986), Maupin (1989), Regan and Harkrider (1989), Cao and Muirhead

(1993), and Gibson and Campillo (1994), using different techniques. A simple geometrical ray theory can be used to predict the kinematic property in a qualitative manner, as Kennett (1986) has illustrated, but would fail to explain the dynamic properties for complex media. Kennett and his associates used a modal summation to investigate $L_g$ propagation in stratified and weakly heterogeneous media. Mitchell and Hwang (1987) computed multi-mode synthetics for 1-D models with various thicknesses of low-Q sediments. Regan and Harkrider (1989) used a hybrid of propagator matrix and finite-element [FE] methods to model the *SH*-$L_g$-wave propagation. Cao and Muirhead (1993) applied a 2-dimensional P-SV finite-difference method to explore $L_g$ blockage and argue that a water column over the crust is an important factor in blocking $L_g$ propagation. Gibson and Campillo (1994) applied both the dynamic ray tracing and the boundary-integral equation methods to model $L_g$ blockage in the west Pyrenees Range, near the French-Spanish border. They suggest that the unmodeled scattering by small-scale features within the lower crust is the reason for the observed blockage. Jih (1995, 1996b) implemented a pure $L_g$ wave packet for Linear Finite Difference (LFD) calculations. This strategy works particularly well for models with additional levels of complexity due to free-surface topographic irregularities and anelastic attenuation. Jih (1996a) (and [3]) pointed out that a shallow, strong attenuative layer near the surface could cause $R_g$-to-higher mode coupling. As a result, some undissipated $R_g$ energy could propagate as crustal S waves like $L_g$. This is rather surprising and seems to be a special mechanism only affecting $R_g$. The significance of the LFD modeling research by Jih and his partners at both former Teledyne Geotech and Phillips Laboratory is that their distinct code permits a convenient investigation of the path effect (due to a specific mechansim) on a specific phase.

# SIGNIFICANT FINDINGS FROM THE SSA MORNING SESSION

From the seven talks from the morning session, there are several observations worth reporting:

[A] With the exception of one theoretical study [3], all the other talks were based primarily on empirical observations. A few of the empirically-based talks were supplemented with minor modeling efforts. The synthetic techniques used include the LFD method (*e.g.*, [2]), ray-tracing (*e.g.*, [5]), and a hybrid method using LFD and locked mode (*e.g.*, [3]).

Several of the authors' results indicate that shallow, lateral crustal heterogeneity can explain much of the variability in high-frequency $L_g$ and long period surface waves in the continents ([1-3],[6]). At least two of the studies indicate that sedimentary basins combined with thinned crust are especially efficient at attenuating $L_g$; such structures are easily modeled using 2D approaches. One question that then arises is how geological structures that are not sedimentary basins can block $L_g$ ([1] used the example of the Tsangpo/Indus suture zone), and how these effects could be modeled.

The principal conclusion reached by the authors of [5] is that strong gradients in Moho topography combined with increasing length of path across such topography correlates well with decreased $L_g$ efficiency. This contrasts with the results from papers [1], [2] and [4], which indicate that Moho topography is a secondary effect compared to upper crustal heterogeneity. One possible explanation for this discrepancy is that the modeling technique (ray-tracing) may bias the author's conclusions towards topography as a predominant cause of surface wave blockage.

[B] While the $L_g$ phase remained the theme of several talks, several PIs have investigated other regional phases such as $R_g$ and $P_n$. This kind of study is important because blockage of one phase in the crustal and/or mantle waveguide is often associated with coupling or conversion to another phase.

For instance, in [3] Jih *et al.* numerically modeled pure $R_g$ using 2D linear finite difference (LFD) and compared a number of physical mechanisms and their effects on waveforms. These mechanisms included rough topography and random heterogeneity. They also looked at $R_g \rightarrow L_g$ conversion in the presence of shallow, highly attenuative layers. The relative effectiveness to block $R_g$ using all three mechanisms was compared. This study provided a clear picture of the expected effect on waveforms using three important and viable physical mechanisms.

In [4] Xie used $P_n$ amplitude variation as an indicator of crustal heterogeneity. He found that $P_n$ variation is much more unpredictable than other phases. It is also more difficult to tell what is causing the variability; it could be a number of mechanisms such as 3-D heterogeneity, caustics at the surface and Moho, or near-surface structural variation. Further study is necessary to quantify which, if any, of these mechanisms can explain the variability in $P_n$.

[C] Many of the presented talks utilized a variety of seismic data sources ranging from recently recovered historical ILPA data ([7]) to data recorded at the newly deployed KNET and CNET ([4,5]). The significance of utilizing these new data sources in regions of great CTBT concern is

that it demonstrates the reliability and usefulness of the new networks. It is hoped that further studies using data from regions of CTBT interest will further complete maps of regional phase blockages and explain some of the mechanisms which cause blockages.

## CONCLUSIONS

$L_g$ phase blockage on the continents appears to be closely tied to upper crustal structure. The modeling and empirical studies show that $L_g$ waves traversing regions with thick sedimentary basins or other strong lateral variations are effectively blocked. A second and, to our minds, less important cause of phase blockage is that of topography, both surface and Moho. Other phases, such as $P_n$, are also sensitive to upper crustal structure and Moho topography, but they are less well understood.

If the empirical studies are done correctly (that is, they separate out the effects on blockage of source mechanism and other forms of attenuation from that due to pure path blockage from topographic or structural variations), they can provide a valuable database or "map" of blockage in regions of CTBT interest. An empirical approach serves the research goal well to the extent of confirming the phase blockage. However, once the blockage is observed in a new region (or, in some cases, a well-studied region), perhaps the effort should be directed towards improving the fundamental understanding of (a) the physical mechanism as well as (b) the possible implication for event discrimination. These two branches generally reflect the difference between 6.1 and 6.2 projects. Obviously from a CTBT-monitoring point of view, it is never enough to "re-confirm" a phase blockage phenomenon. At some point, the PI should move forward to either (a) try to solve the scientific puzzle or (b) find some correction procedure to account for the phase blockage. Either one will improve our capability in monitoring a CTBT in the regional regime. Very often, though, these two goals are intertwined and difficult to separate.

Modeling studies done in conjunction with empirical observations (such as papers [2] and [6]) can reveal the causes of blockage, as long as they use an appropriate modeling technique that can simulate the full wavefield. Studies like [3] are important to understanding the physical mechanisms of a particular type of propagation and blockage, in this case $R_g$.

# RECOMMENDATIONS

In our opinion the problem of phase blockage divides fairly naturally into 6.1 (basic) and 6.2/6.3 (applied) type research programs. A basic research program should be focused on adding to our further understanding of the physical mechanisms of $L_g$, Sn and $P_g/P_n$ blockage. This includes work on establishing the physical basis for discriminants in terms of source mechanism and regional phase excitation. Without a firm foothold in source theory, questions about transportability will continue to go unanswered, particularly in regions where few if any nuclear explosions have been tested before.

Establishing the physical basis can be very difficult because there are usually several competing mechanisms, which can often be coupled and poorly understood. A particularly challenging puzzle concerns the physical basis for the P-to-S ratio and the spectral ratio discriminants. The focus here is primarily on the generation of explosion $L_g$ waves and the role of spall versus the role of $R_g$-to-S conversions.

$R_g$-to-S($L_g$) conversion in the source region is a propagation effect involving a disrupted waveguide or heterogeneity in the medium. On the other hand, explosion $L_g$ may be generated predominantly by intrinsic source mechanisms, especially at high frequencies. (See McLaughlin et al., 1988; Patton and Taylor, 1995; and Jih's talk at this SSA for some aspects of this issue.) This is a typical example of uncertainties in our physical understanding of regional phase excitation due to the (current) inseparability of source and path effects.

A basic research program should also include work on a predictive capability that can model fully 3-D elastic propagation efficiently in the high-frequency (1-10 Hz) regime out to regional distances (1000 km and further). The study of the blockage of other regional phases besides $L_g$ is also important, especially as it relates to location and discrimination.

We think an applied program should complement the basic research studies with projects aimed at empirically mapping blockage in regions of CTBT interest. This could include projects using both historical (such as the ILPA dataset) and current data sets. This type of work will be important in completing the calibration of different regions using regional seismic data. In addition, the applied program is the appropriate place to conduct benchmark tests of different numerical modeling techniques.

Both the basic and applied research programs could involve field studies; however, the design and purpose of these experiments should be very carefully planned. Unless the proposed experiment is carefully designed to solve some specific scientific puzzle, it might end up to be a nonproductive training experiment. During 1995 DoE conducted five field experiments (Stump *et al.*, 1996; DoE, 1996), and the Air Force (PL and AFOSR) also funded at least two experiments. In our opinion it may be preferable to digest the data from these experiments somewhat before more field experiments are conducted.

Possible basic and applied types of field experiments:

**1.** A 6.1 experiment should be designed to solve some fundamental scientific puzzle or issue that is relevant to Air Force's treaty monitoring need. Currently the most important outstanding question is the relationship between near-source media and the mechanics of sources to radiated seismic signals. This type of question cannot be answered by refraction surveys, simply deploying more sensors or making more field trips.

A good example of a relevant 6.1 experiment is the DoE field program led by Brian Stump's group at Los Alamos National Laboratory. During 1995, Stump *et al.* (1996) conducted a series of field experiments with very specific goals attached to each experiment. For instance, his "Source Geometry" experiment was designed to compare spherical (typical of tamped underground nuclear explosion) and cylindrical explosions (typical of mining explosions) and to develop monitoring techniques for both types. In the "Black Thunder" experiment, Stump's research goal was to document the effect of blasting practice on observable seismic signals (see also DoE, 1996).

Although a basic research program like AFOSR's is the ideal vehicle to fund experiments of the 6.1 type, such experiments (like Stump's) are prohibitively expensive. As a result, only very few PIs can be funded to conduct this type of research. What the 6.1 community should do is perhaps to team with Stump and analyze his data jointly, rather than trying to duplicate his experiments at the expense of other fundamental research. Perhaps the funding agencies should make a major field experiment every two or three years a central element of all of the agencies' programs. This would take major coordination efforts among AFTAC, DARPA, DoE, DNA, Phillips Laboratory, and AFOSR, plus potential participants from foreign countries, but the experiment could serve to develop some commonality among the investigators.

**2.** A 6.2/6.3 type of field program should include reconnaissance surveys for regions of monitoring concern that have not been explored well before. Agencies that manage 6.2/6.3 programs should fund studies that attempt to gather useful data to form an usable archive. For this type of experiment, the selection of site is critical, and the basic research program should therefore not be obligated to fund this type of experiment. In fact, if a PI is interested in "calibrating" a region of high monitoring concern through a series of field experiments, the relevant agencies who would use the results had better be consulted in advance.

The worst scenario is for a PI to be funded under 6.1 to conduct an experiment with no scientific goal in mind or funded under 6.2 to conduct experiments in an area of no 6.2 relevance at all. Such experiments are neither a 6.1 nor 6.2 project - they serve at best as a training trip for the technicians. Such experiments bear no relevance to the Air Force's mission and should not be funded by the 6.1 or 6.2 programs, especially when the budgets of these programs are already extremely tight.

# REFERENCES


Bache, T. C., H. Swanger, and B. Shekoller (1981). *Synthesis of $L_g$ in Eastern Uhited States crustal models with frequency independent Q,* Report SSS-R-81-4668. S-Cubed, La Jolla, CA.

Baumgardt, D. R. (1991). *High frequency array studies of long range $L_g$ propagation and the causes of $L_g$ blockage and attenuation in the Eurasian continental craton,* Report PL-TR-91-2059(II), Phillips Laboratory, Hanscom AFB, MA (ADA 236984).

Blandford, R. R. (1981). Seismic discrimination problems at regional distances, in *Identification of Seismic Sources - Earthquake or Underground Explosion,* (E. S. Husebye and S. Mykkeltveit, eds.), D. Reidel Publishing Co., Dordrecht, The Netherlands, 695-740.

Cao, S. and K. J. Muirhead (1993). Finite difference modeling of $L_g$ blockage, *Geophys. J. Int.,* **115,** 85-96.

Gibson, R. and M. Campillo (1994). Numerical simulation of high- and low-frequency $L_g$ -wave propagation, *Geophys. J. Int.,* **118,** 47-56.

Gregersen, S. (1984). $L_g$ -wave propagation and crustal structure differences near Denmark and the North Sea, *Geophys. J. R. astr. Soc.,* **79,** 217-234.

Jih, R.-S. (1995). *Numerical investigation of relative contributions of $R_g$ scattering and attenuation to $L_g$ excitation, in Proceedings of 17th PL/AFOSR Seismic Research Symposium* (12-15 Sept 1995, Scottsdale, AZ; J. Lewkowicz, J. McPhetres, and D. Reiter eds.), Report PL-TR-95-2108, Phillips Laboratory, Hanscom AFB, MA, pp. 401-410.

Jih, R.-S. (1996a). *A simple, causal method to incorporate anelastic attenuation into finite-difference calculations,* Report PL-TR-96-2015, Phillips Laboratory, Hanscom AFB, MA.

Jih, R.-S. (1996b). *Waveguide effects of large-scale structural variation, anelastic attenuation, and random heterogeneity on SV Lg propagation: a finite-difference modeling study,* Report PL-TR-96-2016, Phillips Laboratory, Hanscom AFB, MA.

Jih, R.-S. and C. S. Lynnes (1993). *Studies of regional phase propagation in Eurasia.* Report PL-TR-93-2003 (=TGAL-93-01), Phillips Laboratory, Hanscom AFB, MA (ADA 262801).

Kadinsky-Cade, K., M. Barazangi, J. Oliver, and B. L. Isacks (1981). Lateral variations of high-frequency seismic wave propagation at regional distances across the Turkish and Iranian Plateaus, JGR, **86,** 9377-9396.

Kennett, B. L. (1986). $L_g$ waves and structural boundaries, *Bull. Seism. Soc. Am.,* **76,** 1133-1141.

Kennett, B. L. N., S. Gregersen, S. Mykkeltveit, and R. Newmark (1985). Mapping of crustal heterogeneity in the North Sea Basin via the propagation of $L_g$ waves, *Geophys. J. R. astr. Soc.,* **83,** 299-306.

Levshin, A. and K. A. Berteussen (1979). Anomalous propagation of surface waves in the Barents Sea as inferred from NORSAR recordings, *Geophys. J. R. astr. Soc.*, **56**, 97-118.

Lynnes, C. S. and R. Baumstark (1991). *Phase and spectral ratio discrimination in North America,* Report PL-TR-91-2212(II) (=TGAL-91-06), Phillips Laboratory, Hanscom AFB, MA (ADA 246673).

Maupin, V. (1989). Numerical modeling of $L_g$ wave propagation across the North Sea central graben, *Geophys. J. Int.*, **99**, 273-283.

Nuttli, O. W. (1986). Yield estimates of Nevada Test Site explosions obtained from seismic $L_g$ waves, *J. Geophys. Res.*, **91**, 2137-2151.

Oliver, J. and M. Ewing (1957). Higher modes of continental Rayleigh waves, *Bull. Seism. Soc. Am.*, **47**, 187-204.

Patton, H. J. (1988). Application of Nuttli's method to estimate yield of Nevada Test Site explosions recorded on Lawrence Livermore National Laboratory's digital seismic system, *Bull. Seism. Soc. Am.*, **78**, 1759-1772.

Pomeroy, P. W., W. J. Best, and T. V. McEvilly (1982). Test ban treaty verification with regional data -- a review, *Bull. Seismo. Soc. Am.*, **72**, S89-S129.

Press, F. and M. Ewing (1952). Two slow surface waves across North America, *Bull. Seism. Soc. Am.*, **42**, 219-228.

Regan, J. and D. G. Harkrider (1989). Numerical modeling of *SH* $L_g$ waves in and near continental margins, *Geophys. J. Int.*, **98**, 107-130.

Ruzaikin, A. I., I. L. Nersesov, V. I. Khalturin, and P. Molnar (1977). Propagation of $L_g$ and lateral variation in crustal structure in Asia, *J. Geophys. Res.*, **82**, 307-316.

Stump, B. W., D. C. Pearson, C. L. Edwards, and D. Baker (1996). *Experimental studies for event identification, system calibration, and evasion assessment: a progress report,* Report LAUR-96-1187, EES-3, Los Almos National Laboratory, 28 March 1996.

U.S. Department of Energy (1996). *Nuclear weapon test detection: ensuring a verifiable treaty, (Comprehensive Test Ban Treaty Research and Development Program 1995 Progress Report),* Report DoE/NN-96005281, Department of Energy, Washington, D.C.

Zhang, T. and T. Lay (1994). Analysis of short-period regional phase path effects associated with topography in Eurasia, *Bull. Seism. Soc. Am.*, **84**, 119-132.

## APPENDIX: ABSTRACTS PRESENTED AT PHASE BLOCKAGE SESSION, SSA 91ST MEETING

## $L_g$ Propagation-Path Barriers in the Eurasian Continental Craton -- Possible Shallow Crust Explanations

Baumgardt, D. R., ENSCO, Inc., 5400 Port Royal Rd., Springfield, VA 22151, doug@ensco.com.

Investigations of regional seismic phase propagation in Eurasia, including Scandinavia, Europe, Russia, and China, have revealed numerous instances of anomalous attenuation, or "blockage", of the regional shear phase, $L_g$. Because many regional seismic discriminants used to monitor comprehensive test ban treaties rely on $L_g$ amplitude and spectral measurements, it is important to understand the origin of sudden $L_g$ attenuation.

$L_g$ barriers in the Eurasian continental cratons are related to laterally heterogeneous shallow crustal structure. Such heterogeneities appear to distort the crustal waveguide for $L_g$ and thus produce a sudden blockage of $L_g$ propagation through the anomalous region. In the continents, $L_g$ blockages have been observed for deep sedimentary basins which act as $L_g$ "sinks", *i.e.*, they trap $L_g$ waves which pass through due to strong impedance contrasts between the low-velocity sediments in the basins and granitic-velocity rocks outside of the basins. Crustal thickness variations (e.g., crustal pinchouts) do not seem to be implicated in these blockages since the crustal thickness does not vary by more than 10 km in these regions, even under mountainous regions like the Urals. Examples of such regions include the Barents Sea, Pechora, Caspian Basins, and sedimentary basins around the Urals in Russia.

In China, strong blockage of high-frequency (>1 Hz) $L_g$ has been observed for propagation paths crossing southern Tibet, although $L_g$ does appear to propagate efficiently across northern Tibet. Moreover, low-frequency (<1 Hz) $L_g$ does not seem to be blocked in any of these regions. $L_g$ blockage in Tibet has usually been attributed to anomalous crustal thickness and high anelastic attenuation. Although Tibet is ringed by sedimentary basins, such as the Tarim Basin in the north, the sediment depths are shallow and do not seem to strongly block $L_g$ in the north. However, since many of the blocked $L_g$ paths in southern Tibet cross the Tsangpo/Indus suture zone, a region of anomalous geological structure, it is possible that this suture zone may be a thin boundary in southern Tibet that blocks high-frequency but not low-frequency $L_g$ waves.

These results suggest that lateral heterogeneity in shallow crustal structure may be a major cause of high-frequency $L_g$ blockage in the continents. More observations from new stations now appearing in Eurasia will be needed to more thoroughly map out regions of anomalous $L_g$ blockage in order to explain their origin and to properly calibrate regional discriminants which utilize measurements of the $L_g$ phase.

## Anomalous Surface Wave Propagation across the South Caspian Basin and the Blockage of regional Seismic Phases

K. Priestley, Bullard Laboratories, Univ. of Cambridge, Cambridge CB3 0EZ, United Kingdom, keith@esc.cam.ac.uk, C. Shultz, and H. Patton, Division of Earth Sciences, Lawrence Livermore national Laboratory, CA 94550.

The crust and upper mantle structure of the south Caspian Basin is enigmatic. Early Soviet studies show that the crust of the basin consists of two layers: a thick sedimentary section (15-25 km) with low P-wave velocity (3.5-4.0 km/s) overlying a 12-18 km thick basaltic lower crust. The study of Kadinsky-Cade *et al.* (1981) demonstrated that the seismic phase $L_g$ is largely blocked for paths crossing the south Caspian Basin. New seismic data shows that the south Caspian Basin also severely disrupts low frequency (0.017 -0.10 Hz) fundamental mode surface wave trains. The effect is observed for surface waves propagating along both east-to-west and west-to-east great circle paths showing that this is not a site or instrumental effect. We model the response of the surface wave to this low-velocity sediment, deep basin structure and crustal thinning using a hybrid locked-mode/finite-difference approach. We demonstrate that much of the observed surface wave train degradation can be modeled with the 2-D basin structure. Finally we demonstrate how a simple model of the structure in the Caspian region can help identify blockage mechanism.

**Numerical Modeling of** $R_g$ Blockage and Comparison of $R_g$-to-$L_g$ **Conversion Mechanisms due to Scattering and Incomplete Dissipation**

Jih, R.-S., PL/GPE, Hanscom AFB, MA 01731, jih@snappy.plh.af.mil; McLaughlin, K. L., S-CUBED, La Jolla, CA; Dainty, A. M., PL/GPE, Hanscom AFB, MA; and Harkrider, D. G., Boston College @ PL/GPE, Hanscom AFB, MA.

The presence of a short-period fundamental-mode Rayleigh wave, $R_g$, is an excellent diagnostic for shallow source depth. However, $R_g$ is susceptible to non-uniformities of the near-surface waveguide, and hence absence of $R_g$ does not imply a deep source. Without a predictive capability, the usage of $R_g$ will be limited to well-calibrated source regions and propagation paths. Study of $R_g$ propagation (scattering, attenuation, *etc.*) would naturally help constrain source depth and thereby help event identification also. In this study, intensive linear finite-difference [LFD] calculations are conducted to explore the physical mechanisms of $R_g$ blockage with emphasis placed on quantification of the scattering effects due to rough topography and random heterogeneity. In addition, a new $R_g$ -to- $L_g$ conversion mechanism due to incomplete dissipation by shallow, strong attenuative layers is presented and the relative effectiveness of all three $R_g$-related mechanisms are compared. For models embedded with shallow random heterogeneity, the RMS velocity fluctuation correlates very well with the $R_g$ transmission coefficient. For 1 Hz $R_g$, a 2%–5% variation in the velocity leads to an equivalent spatial Q value of several hundreds or larger, regardless of which of the three commonly used random media is embedded. Rough topography typically results in a Q value ranging from 10 to 100, which is approximately equivalent to a random medium with velocity variation larger than 10%. Incomplete dissipation of $R_g$ waves produces a very simple wave field, with almost all of the undissipated energy propagating laterally towards the forward, and hence postcritical, directions. On the other hand, the scattering by shallow heterogeneity or rough topography generates a rather complicated wave field, with a significant fraction of the scattered energy going steeply downward. In terms of energy partitioning between converted P and S waves, the incomplete dissipation overwhelmingly directs more energy into S ($L_g$) waves, as compared to the remaining two mechanisms. For whichever of the three $R_g$-blocking mechanisms is invoked, the S waves converted from $R_g$ always dominate the whole scattered field.

## Pn amplitude variation along the northern foot of the Tienshan mountains

Xie, J., Lamont-Doherty Earth Observatory, Columbia University, Route 9W, Palisades, NY 10964; 914-365-8553; xie@lamont.ldgo.columbia.edu.

The term "blockage" of regional waveforms has been used to describe drastic amplitude reductions of regional waveforms. This term, however, is typically used in a qualitative and relative sense. For example, blockages of $L_g$ or $S_n$ phases require less amplitude reduction than that of the primary (P) phase since $L_g$ or $S_n$ are preceded by coda of other phases which may have considerable amplitude. In reality, the amplitude of P waves often vary much more drastically than that of the $L_g$ phase, and in a much more unpredictable manner. We present a case in which the Pn phase from Lop Nor explosions undergoes a drastic variation in amplitude (by a factor of 30) across the Kyrghizstan Network (KNET). This network is deployed along the northern foot of the Tienshan mountains and has a relatively small (≈ 100 km) aperture. The amplitude variation primarily occurs at lower (≈ 1 Hz) frequencies, and is accompanied by anomalous polarizations. At station KZA where the largest Pn amplitude is observed, Pn is polarized to N60°W, about 30° away from the great circle. The cause of the amplitude and polarization anomalies are likely to be some deep 3D structural variations, such as Moho topography.

Unlike the Pn amplitude, the $L_g$ amplitude is quite stable across the KNET. This suggests that the amplitude of Pn is much more sensitive to smaller scale variations of crustal structure than that of the $L_g$ phase.

## Regional variations in $L_g$ observed and synthesized at the CNET and KNET arrays

Anderson, T. S., and V. F. Cormier, Dept. of Geology and Geophysics, University of Connecticut, Storrs, CT 06269, tom@geol.uconn.edu, cormier@geol.uconn.edu.

$L_g$ coda seismograms are synthesized as multiple SmS waves in 3-D models of the crust and upper mantle by dynamic ray tracing and summation of Gaussian beams. Results are compared with data from the CNET (Caucasus) and KNET (Kyrgyzstan) arrays, located in regions having significant crustal variations along the borders of the former Soviet Union. Ray diagrams predict weak regional variations in $L_g$ efficiency associated with weak gradients in Moho topography in the Caucasus region. In this region, synthetic seismograms predict crustal thickness variations will have little effect on variations seen across the network. Thus, effects other than crustal thickness variations must be sought to explain strong regional variations in $L_g$ waveforms observed from different azimuths at CNET. Ray diagrams predict much stronger regional variations in $L_g$ efficiency in the Kyrgyzstan region. These variations correlate well with strong gradients in Moho topography along the Hindu Kush and Pamir mountain ranges. Detailed variations of waveforms across the arrays are consistent with $L_g$ efficiency being proportional to the length and number of times SmS ray paths traverse regions of strong Moho gradient.

## Regional Phase Propagation in Northern Africa and the Mediterranean

McNamara, D. E. W. R. Walter, C. Schultz and P. Goldstein, Livermore National Laboratory, Earth Sciences Division, L-205, Livermore, CA 94551.

The Mediterranean region is characterized by abundant seismicity in a complex tectonic environment resulting from the convergence of the African and Asian plates. The purpose of this study is to analyze the propagation characteristics of the high frequency regional phases Pn, Pg, $S_n$ and $L_g$ within North Africa and across the Mediterranean Sea. We have collected regional seismograms from North African earthquakes recorded at MEDNET, GEOSCOPE and IRIS stations in the area. A first look at the data indicates that $L_g$ propagates efficiently to distances of 2000 km or more within Northern Africa but is effectively blocked for most paths crossing the Mediterranean. The picture for $S_n$ is more complicated and shows no clear regional pattern. However unlike $L_g$, $S_n$ is observed on some paths crossing the Mediterranean Sea. These S-wave phases ($S_n$ and $L_g$) are particularly important for algorithms that discriminate small magnitude (Ms < 3.5) underground explosions from earthquakes. Many studies have shown that changes in crustal thickness and/or upper mantle velocity can change or even block the transmission of $S_n$ and $L_g$, greatly complicating the problem of identifying clandestine explosions in such regions. Guided by our empirical data, we make use of 2-D modeling codes to better quantify the types of structures and lengths of paths within those structures, that block these regional phases.

*This research was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.*

## Interpretation of Crustal Phase Characteristics in Iran and the Surrounding Region Determined from ILPA Data

Sweeney, J. J., Treaty Verification Program, Lawrence Livermore National Laboratory, P.O. Box 808, L-208, Livermore, CA, 94550, sweeney3@llnl.gov

The presence or absence of crustal phases such as $S_n$ and $L_g$ at the Iranian Long Period Array (ILPA) show a complex pattern in Iran and the surrounding region. A few degrees of azimuth may mark the boundary between an area where a phase is present and where it is absent. Previous work has identified the southern Caspian region as an area of poor $S_n$ propagation. This study confirms that result and also identifies southeastern Makran, part of the Iran plateau, and part of the Zagros region as areas where the $S_n$ phase is absent. In general, lack of an $S_n$ phase can be associated with paths crossing regions of Quaternary and Tertiary volcanism. $L_g$ propagation is present over most of Iran with the exception of the Zagros region between the Oman line and Qatar. This is an area with extensive mobile infra-Cambrian salt. Other regions identified with no $L_g$ phase are the Caspian and Black Sea areas, which have been noted by other workers.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48. Multimax Corp. supplied the data for this study.*

## DISTRIBUTION LIST

Dr. Douglas R. Baumgardt
ENSCO, Inc.
5400 Port Royal Road
Springfield, VA 22151

Dr. Jiakang Xie
Lamont-Doherty Earth Observatory
of Columbia University
Palisades, NY 10964

Dr. Howard Patton, Dr. Dan McNamara,
Dr. William Walter Dr. Craig Schultz,
Dr. Peter Goldstein, Dr. Jerry Sweeney
Lawrence Livermore National Laboratory
P.O. Box 808, L205
Livermore, CA 94550 (6 copies)

Prof. Vernon F. Cormier
Dept. of Geology & Geophysics
University of Connecticut
Storrs, CT 06269-2045

Prof. Keith Priestley
Dept. of Earth Sciences
Madingley Rise, Madingley Road
University of Cambridge
Cambridge CB3 0EZ, ENGLAND

DARPA/OASB/Librarian
3701 N. Fairfax Drive
Arlington, VA 22303-1714

Dr. Ralph W. Alewine, III
Dr. Steven R. Bratt
Nuclear Treaty Programs Office
Rosslyn Gateway
1901 N. Moore Street, Suite 609
Arlington, VA 22209 (2 copies)

Dr. Robert R. Blandford
AFTAC/TT, Center for Monitoring Research
1300 N. 17th Street, Suite 1450
Arlington, VA 22209

Defense Technical Information Center
8725 John J. Kingman Road
Fort Belvoir, VA 22060-6218 (2 copies)

Dr. Delaine T. Reiter, Mr. Rong-Song Jih
Earth Sciences Division (PL/GPE)
Phillips Lab./ Geophysics Directorate
Hanscom AFB, MA 01731 (2 copies)

Dr. Stanley K. Dickinson
AFOSR/NM
110 Duncan Avenue, Suite B115
Bolling AFB
Washington, DC 20331-6448

Dr. Dale Glover
U.S. DIA/DT-IB
Washington, DC 20301

HQ AFTAC/CA
(STINFO)
1030 South Highway A1A
Patrick AFB, FL 32925-6001

HQ AFTAC/TTR
1030 South Highway A1A
Patrick AFB, FL 32925-6001 (12 copies)

HQ AFTAC/TTD
1030 South Highway A1A
Patrick AFB, FL 32925-6001 (3 copies)

Dr. Max Koontz, Ms. Joan B. Rohlfing
Ms. Leslie A. Casey, Dr. Stan Rudnick
U.S. Dept. of Energy/NN-20
Forrestal Building
1000 Independence Avenue
Washington, DC 20585 (4 copies)

Dr. Leonard E. Johnson
National Science Foundation
Division of Earth Sciences
4201 Wilson Boulevard, Suite 785
Arlington, VA 22230

Dr. William S. Leith
Mr. John Rodney Matzko
U.S. Geological Survey
920 National Center
Reston, VA 22092 (2 copies)

Earth Sciences Division (PL/GPE)
Phillips Lab/Geophysics Directorate
Hanscom AFB, MA 01731

Dr. Don A. Linger, Dr. Michael Shore
U.S. DNA
6801 Telegraph Road
Alexandria, VA 22310 (2 copies)

Dr. Robert P. Massé
Denver Federal Center
Box 25046, Mail Stop 967
Denver, CO 80225

Phillips Laboratory / TL
5 Wright Street
Hanscom AFB, MA 01731

Phillips Laboratory
PL/SUL
3550 Aberdeen Avenue, SE
Kirtland AFB, NM 87117 (2 copies)

Center for Verification Research
Technical Library
P.O. Box 1148
8500 Cinder Bed Road
Newington, VA 22122-9998